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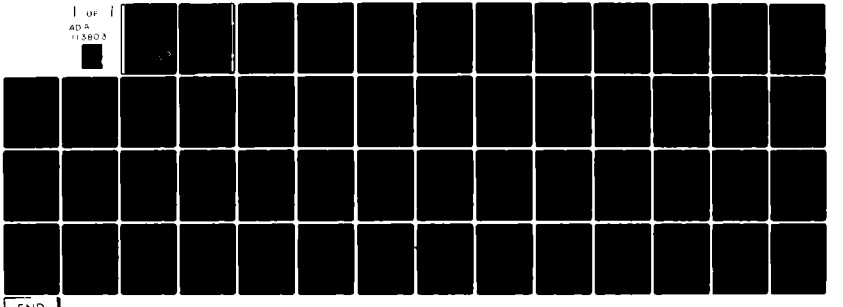

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FEASIBILITY OF INSPECTING ADHESIVE BONDED STRUCTURES FOR BOND STRENGTH USING ULTRASONIC SPECTROSCOPY

March 1982

T. J. IGIELSKI, S. S. BLECHERMAN, and J. E. DOHERTY
Pratt & Whitney Aircraft Group
Government Products Division
West Palm Beach, Florida 33402

FINAL REPORT

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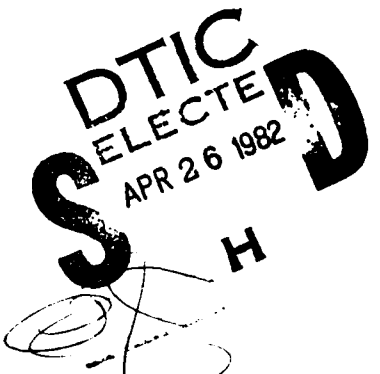

Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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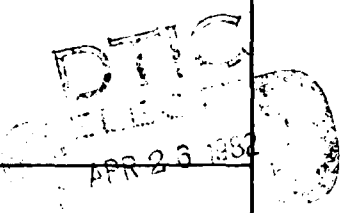

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A study for using ultrasonic spectroscopy as a nondestructive evaluation method for determining the integrity of adhesive bonds between composite materials and metals was evaluated. Mechanical properties of bonded joints were compared to acoustic parameters for various adhesive substrate systems.

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SUMMARY

Structural adhesive materials are being used extensively to bond main and tail rotor blades as well as other sections of helicopter aircraft. Improvements in adhesive bond line inspection sensitivity levels and a correlation to joint strength are desirable, especially in highly stressed rotating parts. In this program, specimens were fabricated of typical rotor blade bonded joint materials such as fiberglass-epoxy to aluminum and graphite-epoxy to titanium. The joint geometry was also simulated to represent both a continuous and discontinuous bond line separated by parallel channels. Adhesive material containing "low" and "high" initial water content was used to simulate the quality variations that might occur in the bond line. Furthermore, bond joint thickness and as-received adhesive porosity content were varied. For each combination of adhesive material variation, bond quality, and joint thickness, a correlation was made between an acoustic spectroscopy parameter and mechanical properties as measured by lap-shear durability strength or joint ultimate strength if the durability test specimen did not fail.

The results of the graphite-epoxy titanium bonded joint specimen test program indicated that adhesive joint porosity variations did not provide significant acoustic signal differences. Neither joint thickness nor porosity could be correlated with a change in lap-shear strength durability. However, a slight but noticeable trend did exist between acoustic parameters and mechanical properties for thick bonds in both the "dry" and the "wet" condition. Fiberglass-epoxy aluminum joints showed good acoustic signal separation characteristics between "dry" and "wet" content adhesives and a good correlation to lap shear stress durability data. However, no comparisons between specimens with thick bonds versus thin bonds could be made for these materials. Specimens fabricated with open parallel channels between the bonded areas did not yield acoustic signals because of extremely thin adhesive in the bond line. The limited number of specimens evaluated for each combination of material and the small inspectable surface area of 1 sq inch for each specimen prevented a determination of statistical trends that might be present in bonded areas of larger parts.

A plan for a computerized adhesive inspection system based upon acoustic spectroscopy was developed. This plan included a specification for a prototype inspection system capable of being used for the collection and correlation of additional adhesive bonded joint data.

PREFACE

This investigation was conducted for the Army Materials and Mechanics Research Center, Watertown, Massachusetts under Contract DAAG46-79-C-0039 by Pratt & Whitney Aircraft Group. The technical effort was conducted in the Middletown, Connecticut facility. The internal report number is PWA-5868.

Dr. J. E. Doherty was project manager and Mr. S. S. Blecherman, senior program manager. Mr. T. J. Igielski conducted the overall technical evaluation. The authors of this report acknowledge the efforts of Mr. P. Meck, Sikorsky Aircraft, for fabrication, mechanical testing, and technical evaluation of the test specimens used in this program.

Dr. J. M. Smith was project manager for the U.S. Army, and Mr. G. A. Darcy, NDE branch chief.

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1.0 INTRODUCTION

The use of adhesive bonding to fabricate structures has become more prevalent with the need to reduce the weight of flight systems. The increased use of adhesive bonds in critical components has focused attention on the methods used to inspect and evaluate bonded joints. Current practice has evolved process control methods which monitor the individual steps in bond fabrication and nondestructive methods to check for the presence of bonds in finished components. Successful structures and components have been made using these approaches. Nevertheless, the only method currently available to determine whether or not an adhesive bond of adequate strength has been produced is by destructive testing. Consequently, there is a need for a truly nondestructive method of measuring the strength of adhesive bonds.

Pratt & Whitney Aircraft, with Sikorsky Aircraft as subcontractor, has completed a program to evaluate ultrasonic spectroscopy as a method for determining strength of adhesive bonds in composite structures. The object was to determine whether there were test parameters that could be related to strength in adhesive bonds. These parameters would serve as the basis for the design of an instrument for evaluating adhesive bonds.

Section 3 describes the process variables and the methods used to fabricate the various types of lap-shear test specimens. Each type of specimen is listed, together with the location of a similar configuration on the BLACK HAWK helicopter. This section also describes the mechanical testing procedure and the method of acoustic spectroscopy used to measure the experimental data.

Section 4 describes the results of mechanical testing along with observations about the mode of failure. This section also contains the results of the ultrasonic spectrographic measurements and the technical problems associated with the measurement technique.

Section 5 relates the results of mechanical testing to spectrographic measurements and process variants. Exceptions to general trends described in the data and conclusions are also explained.

Section 6 describes a development plan for a prototype adhesive inspection system. The description of the hardware is explained at the module level, and software is detailed at the measurement system mode level.

2.0 EXPERIMENTAL PLAN

This section describes the types of specimen configurations, materials comprising the specimens, and the process variables used in manufacturing the specimens. The acoustic spectroscopy measurement system is also described, and details associated with the mechanical test procedure are explained.

2.1 Specimen Configurations and Materials

The overlap tensile shear specimens were fabricated into three configurations as shown in Figure 1. The specimens model adhesive bonds, which are used at the following locations in the Black Hawk helicopter:

(1) Fiberglass skin to Blade Inspection Method (BIM^{R}) blanket to titanium spar bond used on the main rotor blade.

(2) Graphite spar to titanium fitting bond used on the tail rotor blade.

(3) Fiberglass skin to aluminum bond used on the tail rotor blade.

2.2 Normal Process Variables

Sections 2.2.1 through 2.2.4 list the materials and describe the composite and adhesive cure conditions, surface preparation, and bonding used to manufacture the overlap tensile shear specimens. These process variables are for normal manufacturing conditions. Process variables which were changed for the purpose of altering the adhesive bond are described in section 2.3.

2.2.1 Materials

The following materials were used to fabricate test specimens and are identical to the materials used on the BLACK HAWK rotor blades.

(1) Fiberglass-epoxy: SP-114, 3M Company, St. Paul, Minn.

(2) Graphite-epoxy: RAC 6350/AS, Ciba-Geigy, Fountain Valley, Ca.

(3) Adhesive: M1113, Narmco Materials, Costa Mesa, Ca.

(4) Primer: M6726, Narmco Materials, Costa Mesa, Ca.

(5) Titanium: MIL-T-9046, Type III, Composition C or D (6Al-4V).

(6) Aluminum: QQ-A-250/5 alclad 2024 sheet.

FIGURE 1.a FIBERGLASS EPOXY-BIM^{R}-TITANIUM

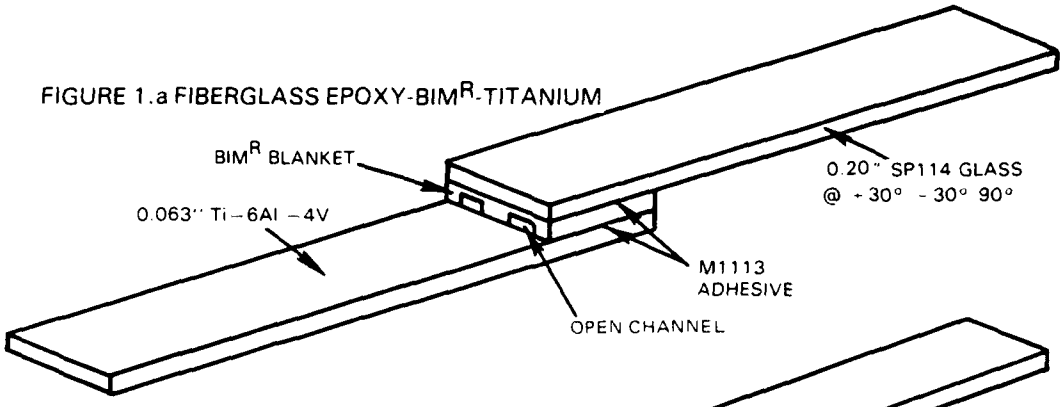


FIGURE 1.b GRAPHITE EPOXY-TITANIUM

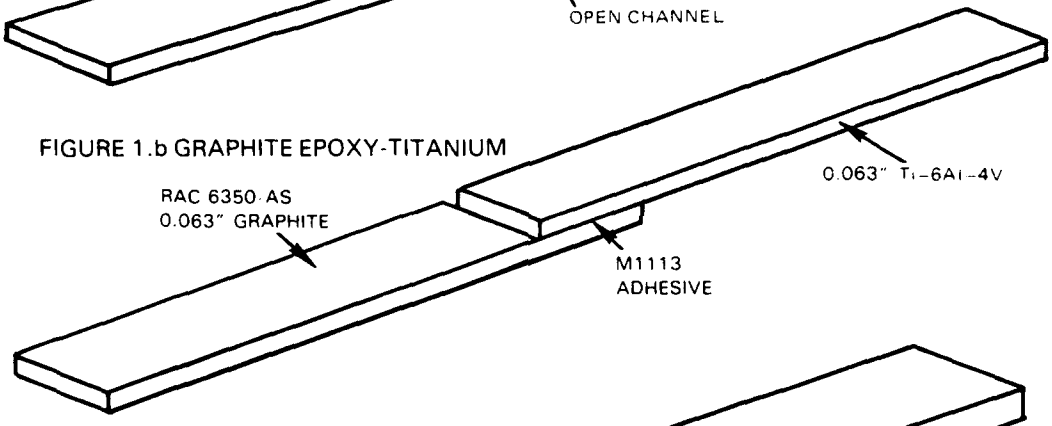


FIGURE 1.c FIBERGLASS EPOXY-ALUMINUM

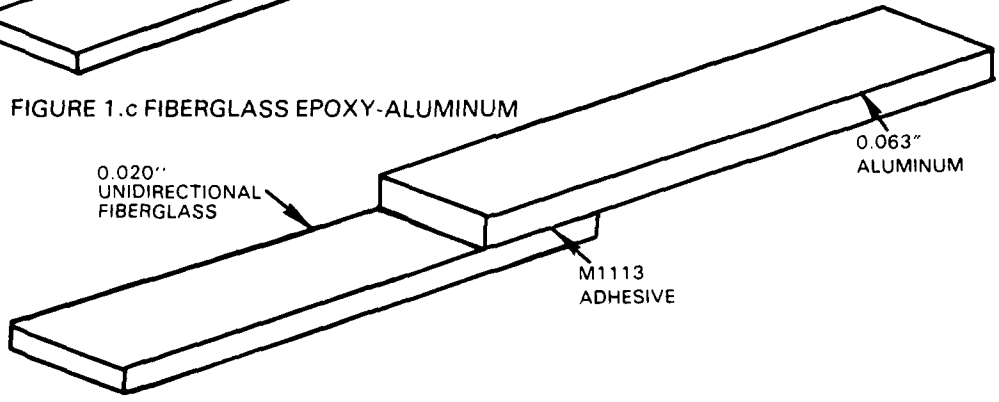


Figure 1 Lap Shear Specimen Configurations

2.2.2 Composite and Adhesive Cure Conditions

(1) Fiberglass-epoxy, SP-114 was cured at 360 F (±10 F) for 120-130 minutes at 60-70 psi.

(2) Graphite-epoxy, RAC 6350/AS was compacted at 180 F and then cured at 350 F (±10 F) for 120-130 minutes at 100 psi.

(3) M6726 primer, applied to both titanium and aluminum, was air dried for 30 minutes minimum at room temperature plus 55-60 minutes at 250 F (±10 F).

(4) M1113 adhesive was cured at 250 F + 20 F/-10 F for 60 (±5) minutes at the required pressure.

2.2.3 Surface Preparation

1. Both the SP-114 fiberglass and the RAC 6350/AS graphite were laminated into sheets with nylon peel ply on the bond surfaces. The sheets were cut to the required dimension and the peel ply was removed at the time of bonding. The adhesive was applied immediately after the removal of the peel ply.

2. Titanium was shot-peened to production requirements and then Picatinny etch treated. This is the modified phosphate-flouride prebond treatment of titanium developed by the Department of the Army, Picatinny Arsenal and incorporated into Sikorsky's Specification SS8461. After prebond treatment, the metal was oven dried at 130-150 F for 10-20 minutes and primed. Oven-drying and priming were accomplished within 4 hours of prebond treatment.

3. Aluminum was chromic acid anodized per MIL-A-8625, except that the anodize was not sealed. The metal was oven dried at 130-150 F for 10-20 minutes and primed. Oven-drying and priming were accomplished within 8 hours of removal from the anodize tanks.

2.2.4 Bonding

All specimens were bonded with one layer of 0.06 weight nylon scrim supported M1113 adhesive, with the exception of the BIM^{R} lands to titanium. In the BIM^{R} to titanium bonds, 0.03 weight of nylon scrim supported adhesive was used.

2.3 Variable Bond Properties

Three processing variants were used in the fabrication of the lap-shear specimens:

(1) Low and specification level bonding pressure to achieve thick and thin bonds, respectively

(2) Wet adhesive

(3) Porosity in adhesive

Two bonding pressures (50 psi and 5 psi) were used to manufacture the specimens. Specimens that required 50 psi pressure were bonded in an autoclave; those requiring lower pressure were bonded with a dead weight load in an oven. The adhesive for "wet" specimens was conditioned for 24 hours at 140 F and 95-100 percent relative humidity.

Initially, small glass spheres were used to simulate porosity. An alternate method, which utilized the selection of uncured adhesive with large amounts of air bubbles, was also used to simulate porosity.

The combinational matrix for the process variants for each configuration is shown in Table 1 on page 12. Each configuration consists of twenty-four specimens, divided into eight groups of three specimens. The specimens in each configuration, numbered 1-3, have no process variants and serve as the control group.

TABLE 1

COMBINATIONAL MATRIX OF PROCESS VARIANTS

(a) Fiberglass-BIM^{R}-Titanium Configuration

	Specification Quality Adhesive		Porous Adhesive[1]	
Pressure (psi)	50	5	50	5
Specimen No.				
Dry Adhesive	1-2-3	4-5-6	7-8-9	10-11-12
Wet Adhesive	13-14-15	16-17-18	19-20-21	22-23-24

(b) Graphite Epoxy-Titanium Configuration

	Specification Quality Adhesive		Porous Adhesive[2]	
Pressure (psi)	50	5	50	5
Specimen No.				
Dry Adhesive	1-2-3	4-5-6	7-8-9	10-11-12
Wet Adhesive	13-14-15	16-17-18	19-20-21	22-23-24

(c) Fiberglass Epoxy-Aluminum Configuration

	Specification Quality Adhesive		Porous Adhesive[1]	
Pressure (psi)	50	5	50	5
Specimen No.				
Dry Adhesive	1-2-3	4-5-6	7-8-9	10-11-12
Wet Adhesive	13-14-15	16-17-18	19-20-21	22-23-24

(1) Porosity simulated by small glass spheres
(2) Porosity simulated by selection of adhesive with air bubbles

2.4 Acoustic Spectroscopy Testing Procedure

A block diagram of the measuring system, which was used to ultrasonically test lap-shear specimens, is show in Figure 2. The pulser excites the acoustic transducer, which is coupled to the specimen. Returning echoes are amplified by the receiver. The stepless gate allows the operator to choose the receiver output signals to be analyzed by the spectrum analyzer. The spectrum analyzer was adjusted to analyze frequencies in the range of 2-20 MHz.

An oscilloscope monitors the input and output signals of the stepless gate as the operator makes adjustments to the stepless gate. The output of the spectrum analyzer is a pulsed signal. A peak detector was used to convert this pulsed signal to a static voltage which is compatible with the computer interface. The keyboard and display provide for communication with the software, and the plotter provides a hard copy of the data.

Ultrasonic measurements were made using a Harrisonic's No. DG 1504 15 MHz, 0.25-in contact transducer from the composite side of the specimens. The acoustic couplant was an Automation Industries "Multi-Purpose Ultrasonic Couplant" (medium viscosity). The stepless gate was adjusted to pass only the front surface and back surface return echoes from the adhesive (Figure 3). This adjustment was made prior to analyzing each signal. Special care was taken to position the transducer such that the measurement was reproducible.

2.5 Mechanical Testing Procedure

Twelve fiberglass epoxy-aluminum and twenty-four graphite epoxy-titanium specimens were tested and evaluated by Sikorsky Aircraft for stress durability at elevated temperature and humidity. The initial load was 2300 psi at a test temperature of 140 F and relative humidity of 95 percent. If a specimen did not fail within 329 hours (graphite epoxy-titanium) or 454 hours (fiberglass epoxy-aluminum), it was removed from the testing jig and tested to failure for residual lap-shear strength.

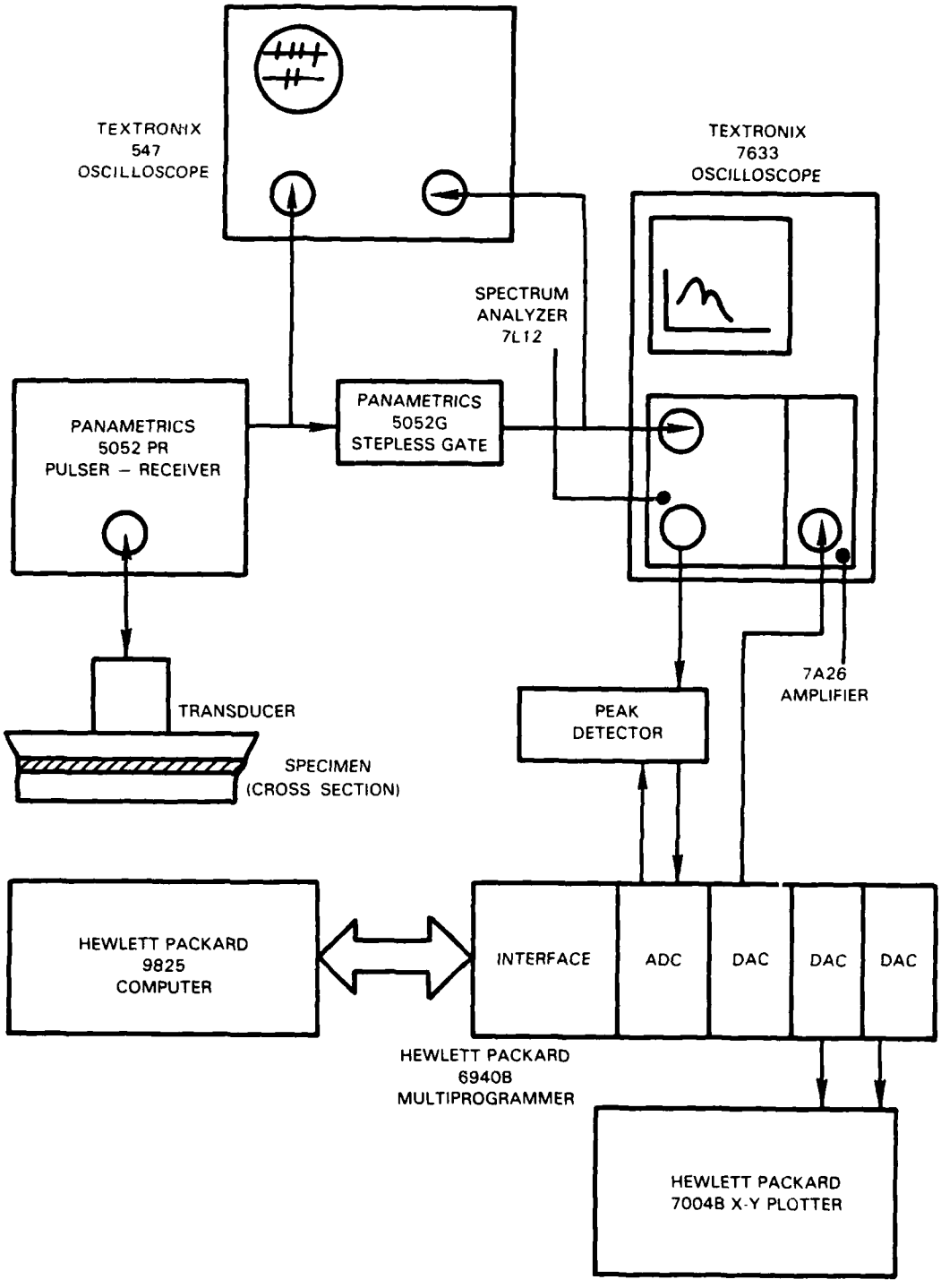


Figure 2 Block Diagram of Acoustic Spectroscopy Measurement System

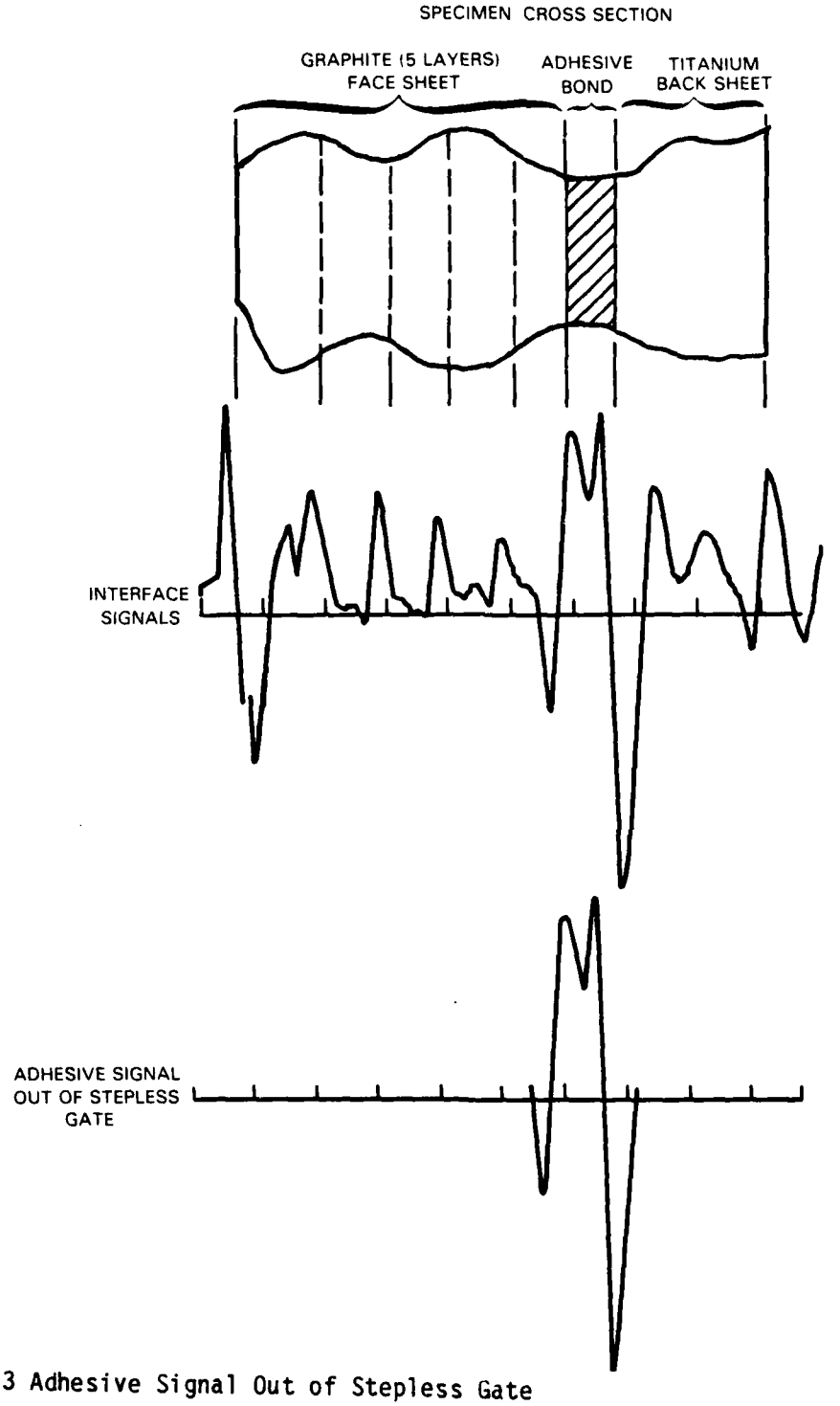


Figure 3 Adhesive Signal Out of Stepless Gate

3.0 TEST RESULTS - SUMMARY

Acoustic and mechanical test results for graphite-titanium and fiberglass-aluminum joints are presented in Tables 2, 3, 4, and 5. Observations about the mode of failure and the results of the ultrasonic spectrographic tests are discussed in section 4.1.

TABLE 2

GRAPHITE EPOXY-TITANIUM PROCESS VARIANT MATRIX WITH MECHANICAL TEST RESULTS

Lap-Shear Residual Strength (psi) After Stress Durability Test(1)

	Adhesive Selected for Few Air Bubbles				Adhesive Selected for Many Air Bubbles			
	Specification Bonding Pressure, 50 psi		Low Bonding Pressure, 5 psi		Specification Bonding Pressure, 50 psi		Low Bonding Pressure, 5 psi	
	Thin Bond		Thick Bond		Thin Bond		Thick Bond	
Low Humidity "Dry" Specimens	1	5544	4	5063	7	4710	10	5290
	2	5034	5	5281	8	4759	11	4788
	3	5615	6	----	9	4950	12	5123
	Avg	5400	Avg	5172(2)	Avg	4806	Avg	5063
High Humidity "Wet" Specimens	13	5731	16	3771	19	4913	22	4535
	14	4204	17	5071	20	4753	23	3206(3)
	15	4143	18	4157	21	4988	24	4278
	Avg	4692	Avg	4333	Avg	4874	Avg	4006
			Excessive Post-Test Porosity				Excessive Post-Test Porosity	

(1) No failure after stress durability test at 2300 psi; 140 F; 95 percent relative humidity; 329 hr
(2) Average of two values only, specimen 6 failed stress durability in 9 hours.
(3) Specimen 23 has a low shear load value.

TABLE 3

FIBERGLASS EPOXY-ALUMINUM PROCESS VARIANT MATRIX WITH MECHANICAL TEST RESULTS

	Specification Bonding Pressure, 50 psi		Low Bonding Pressure, 5 psi	
	Thin Bond		Thick Bond	
	Lap Shear Strength, psi(1)			
Low Humidity "Dry" Specimens	1	2370	4	2850
	2	2330	5	2900
	3	2380	6	3180
	Avg.	2360	Avg.	2976
	Hours to Failure(2)			
High Humidity "Wet" Specimens	13	33	16	69
	14	23	17	40
	15	27	18	85
	Avg.	27	Avg.	65
	High Post Test(3) Porosity		High Post Test(3) Porosity	

(1) Residual Tensile Strength (psi) at room temperature after stress durability exposure at 2300 psi; 140 F; 95 percent relative humidity; 454 hr.

(2) Hours to failure at stress durability conditions described in (1).

(3) Specimens did not have intentional porosity as the process variant; however, porosity was higher than expected.

TABLE 4

GRAPHITE EPOXY-TITANIUM PROCESS VARIANT MATRIX WITH ACOUSTIC RESULTS

	Adhesive Selected for Few Air Bubbles		Adhesive Selected for Many Air Bubbles	
	Specification Bonding Pressure, 50 psi	Low Bonding Pressure, 5 psi	Specification Bonding Pressure, 50 psi	Low Bonding Pressure, 5 psi
	Thin Bond	Thick Bond	Thin Bond	Thick Bond
Low Humidity "Dry" Specimens	Spec 1, 2, 3	Spec 4, 5, 6	Spec 7, 8, 9	Spec 10, 11, 12
Avg. Resonant Depth(1)	9.3	17.0	8.0	20.0
Energy Beyond Resonance	177	302	203	267
High Humidity "Wet" Specimens	Spec 13, 14, 15	Spec 16, 17, 18(2)	Spec 19, 20, 21	Spec 22, 23, 24(2)
Avg. Resonant Depth(1)	10.7	22.7	11.3	24.7
Energy Beyond Resonance	207	369	169	327

(1) Acoustic parameters (average value for three specimens) are resonant depth (unitless parameter).

(2) Excessive bond line porosity.

TABLE 5

FIBERGLASS EPOXY-ALUMINUM PROCESS VARIANT MATRIX WITH ACOUSTIC RESULTS

	Specification Bonding Pressure, 50 psi	Low Bonding Pressure, 5 psi
	Thin Bond	Thick Bond
Low Humidity "Dry" Specimens		
Specimen No.	1,2,3	4,5,6
Avg. Resonant Depth(1)	16.0	18.7
Energy Beyond Resonance	94	184
High Humidity "Wet" Specimens		
Specimen No.	13,14,15(2)	16,17,18(2)
Avg. Resonant Depth(1)	10.0	7.7
Energy Beyond Resonance	39	73

Specimens did not have intentional porosity as the process variant.

(1) Acoustic parameters (average value for three specimens) are resonant depth.

(2) Excessive bond line porosity.

3.1 Mechanical Test Results

Twenty-three of the twenty-four graphite-titanium specimens survived stress durability without failure, indicating the joint systems were tolerant of the porosity and moisture-induced bond line deficiencies.

All of the "dry" fiberglass-aluminum specimens endured stress durability without failure. All of the "wet" fiberglass-aluminum specimens failed early in the test. The failed lap-shear specimen surfaces, showing the effects of adhesive and bonding process variations on joint porosity, are shown in Figure 4.

3.1.1 Graphite Epoxy-Titanium

Mechanical testing data are presented in Table 2 for graphite-titanium joints using the master format shown in Table 1(b). Specimen 6 failed in stress durability in only 9 hours. The failure mode was adhesive to the metal, and 75 percent of the adhesive/primer combination came clean of the metal. The residual strength for the remaining specimens were considered acceptable on the basis of past experience except for specimen 23, which indicated contamination on the metal in the areas where the adhesive/primer separated from the metal. Six specimens, which had "wet" thick bonds, had more porosity than the other eighteen, but the tensile failure loads were considered acceptable.

Normal specimens without process variants showed the highest average strength. Specimens associated with thick bonds and "wet" adhesive had excessive porosity and the lowest average residual strength. The mechanical strength data of individual specimens was not sufficiently uniform to separate out the process variants according to strength.

3.1.2 Fiberglass Epoxy-Aluminum

Mechanical testing data are presented in Table 3 for fiberglass-aluminum joints using the left half of the master format of Table 1c. The data for the specimens from the right half of the table have been omitted. Specimens associated with these data were manufactured with small glass spheres in the adhesive bond which were to simulate porosity. The data for these specimens, however, were rejected because physical properties of glass did not produce a change in the acoustic parameters similar to a "wet" porous bond.

The "wet" specimens had a high degree of porosity in the bond line and failed early in the stress durability test.

3.2 Results of Ultrasonic Spectrographic Tests

Ultrasonic spectroscopy data were obtained by a measuring technique used in previous studies on metal-to-metal adhesive bonds. The measured spectrum parameters (illustrated in Figure 5) are:

(1) Resonant Frequency
(2) Resonant Depth
(3) Energy Above Resonance

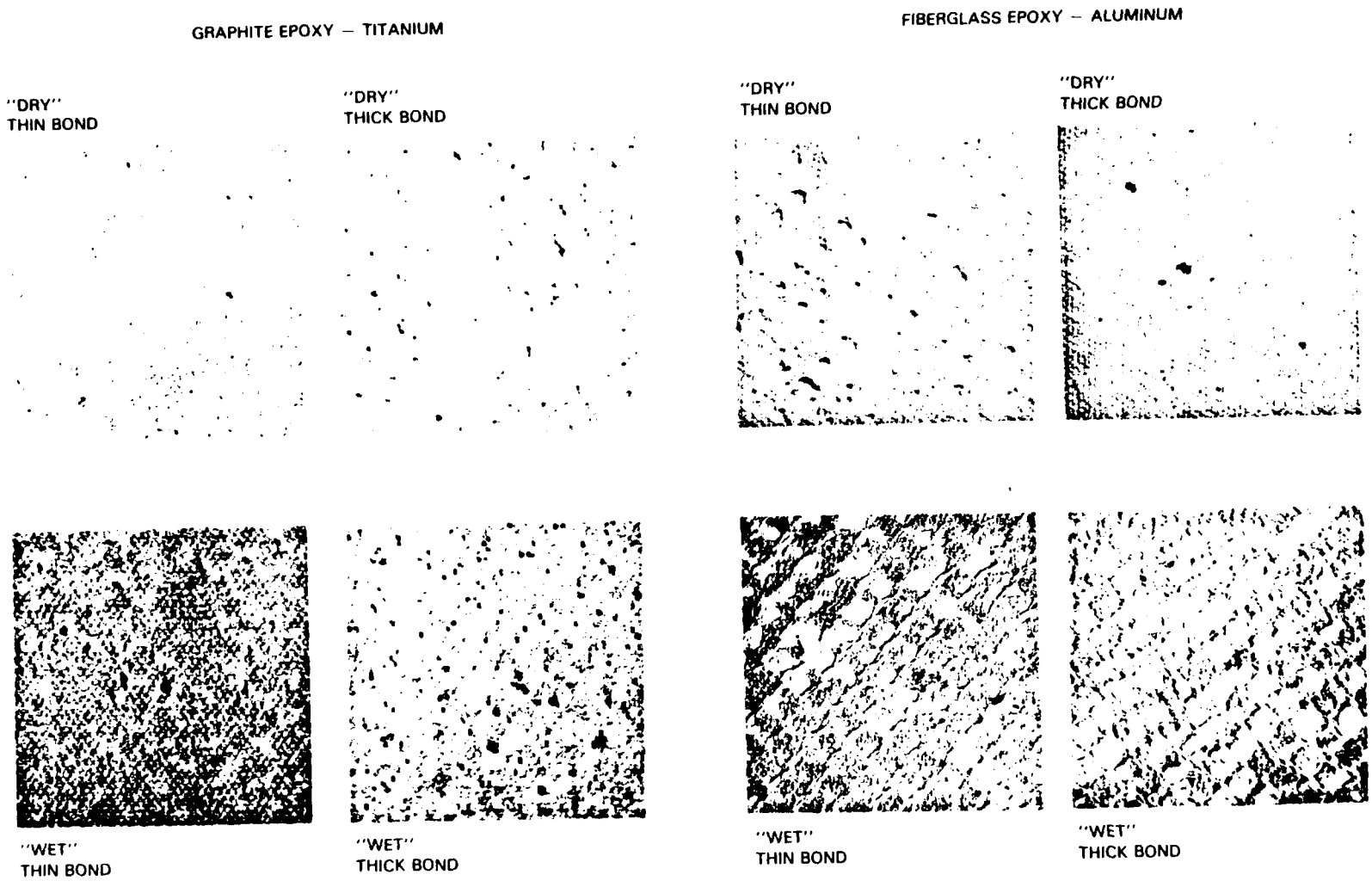


Figure 4 Effects of Adhesive and Bonding Process Variations on Joint Porosity

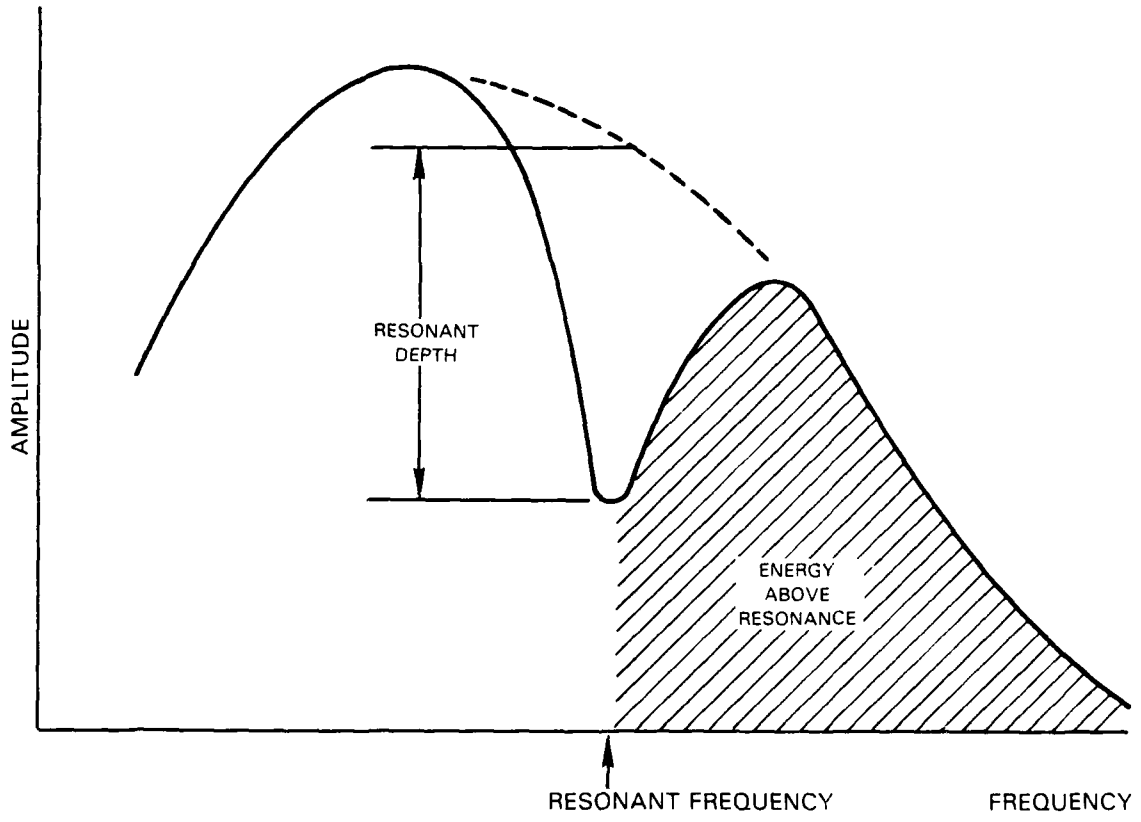


Figure 5 Acoustic Spectrum (Measurement of Acoustic Parameters)

These acoustic parameters were measured from ultrasonic spectra without the benefit of the deconvolution technique, which would have divided out the frequency dependent effects (transducer bandwidth, electronic system bandwidth) from the adhesive bond ultrasonic spectrum.

To perform the deconvolution, the composite-adhesive signal (which is used to obtain the reference spectrum) must be completely separated from the adhesive-metal signal. These signals are shown in Figure 6 for thick and thin adhesive bonds. The complex nature of the composite face sheet material provided an additional frequency dependent factor which limited the ability of the measurement system to separate the adhesive bond signals. Thin adhesive bonds are more severely affected by the reduction in measurement bandwidth caused by the composite face sheet.

The effect of the composite (graphite) face sheet on the frequency response of the acoustic signal is illustrated in Figure 7. The impulse that was coupled to the graphite face sheet (A) had a wide bandwidth. The graphite attenuates high frequencies and produces an impulse at the face sheet/adhesive interface with a reduced bandwidth (B). The combined response of the measurement system and the composite face sheet does not have enough bandwidth to completely separate the signals that define a thick adhesive bond. Failure to resolve this interface signal in time means that the signal cannot be analyzed to obtain the reference spectrum necessary to perform the deconvolution.

Because the deconvolution technique was not used, the spectrum parameters (resonant depth and energy above resonance) were biased by the face sheet frequency response. The effect of the face sheet response on the acoustic parameters is depicted in Figure 8. The measurements for thick bonds are characterized by large values of resonant depth and energy beyond resonance because the resonant depth was located at the largest amount of power. As the adhesive bond decreased in thickness, the resonant frequency increased to a location in the spectrum where the power was reduced, and, therefore, the measured amplitude of resonant depth and the energy above resonance was reduced.

To allow for the thickness bias, which was caused by the position of the resonant depth in the power spectrum, only comparisons between specimens of approximately equal thickness were made.

The measured acoustic parameters for graphite-titanium and fiberglass-aluminum are shown in Tables 4 and 5, respectively. The resonant frequency is inversely proportional to the adhesive bond thickness, if the adhesive signals can be completely separated. Because of the measurement limitations already stated, bond thickness was determined indirectly by acoustically measuring the composite face sheet and metal back sheet thicknesses. The sum of these two values was subtracted from the overall mechanical thickness. The results were then categorized as thick or thin bonds. Resonant depth and energy above resonance were measured directly from the adhesive bond spectra.

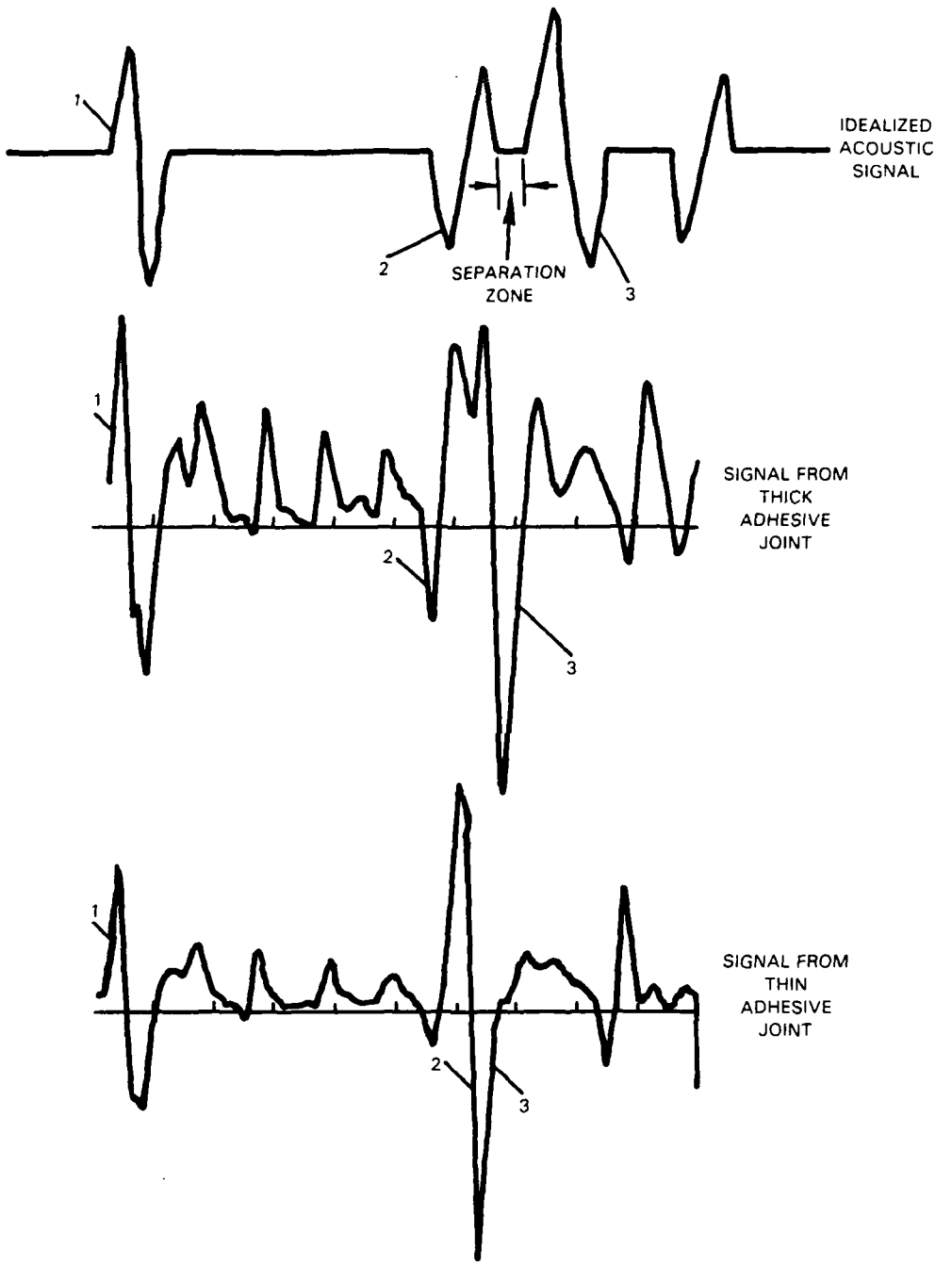


Figure 6 Acoustic Signals for Thick and Thin Adhesive Bonds - The impulse originates at the composite face sheet (1). Adhesive bonds signals (2 and 3) are completely separated for the idealized acoustic signal. The signals start to merge as the bond line decreases in thickness as shown in the intermediate sketch. In the last diagram, separate signals cannot be distinguished for the thin adhesive joint.

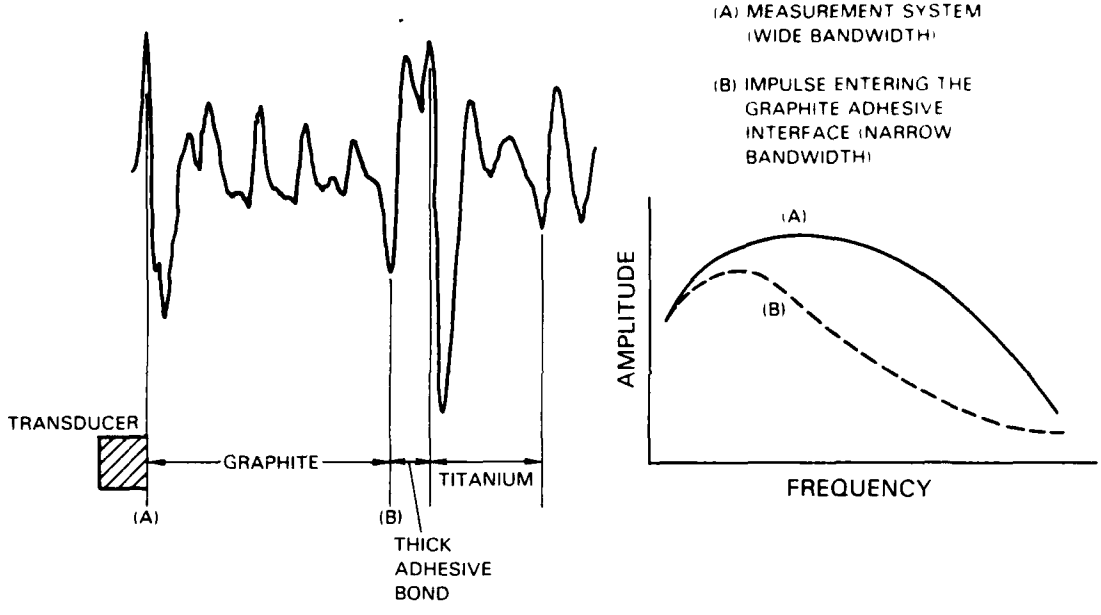


Figure 7 Effects of Composite Face Sheet on Acoustic Spectrum - The impulse at (A) has a wide bandwidth. The impulse at (B) has a bandwidth which has been reduced by the frequency dependent attenuation of the graphite face sheet. The narrow bandwidth was insufficient to separate the adhesive signals of a thick bond.

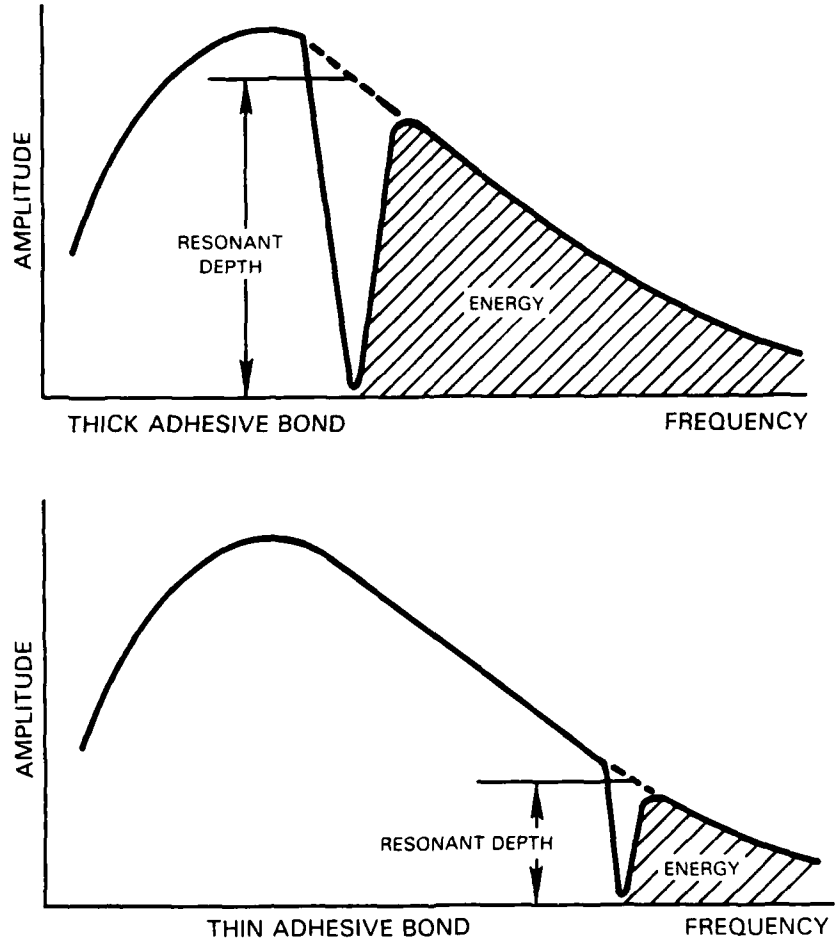


Figure 8 Illustration of the Effect of the Measurement System on Spectrum Parameters for Specimens with Thick and Thin Bonds

3.2.1 Graphite Epoxy-Titanium

The acoustic parameters (see Table 4) associated with thin and thick adhesive bonds have smaller values for "dry" specimens than for "wet" specimens. The parameter difference between "dry" and "wet" specimens was not large, especially for thin adhesive bonds.

3.2.2 Fiberglass Epoxy-Aluminum

The acoustic parameters (Table 5), associated with thin and thick bond lines, have larger values for "dry" specimens than for "wet" specimens. This was the opposite effect compared to the acoustic parameters for graphite-titanium (Table 4).

3.2.3 Fiberglass Epoxy-BIM -Titanium

BIM^R specimens were manufactured with a complex multi-layered (fiberglass-fiberglass BIM^R BLANKET-titanium) adhesive system (see Figure 1(a)). These specimens could not be tested because the adhesive signal could not be recognized. These specimens were manufactured with thin adhesives that flowed into the parallel channels of the BIM^R BLANKET and formed thinner bonds than occurred for the other specimen configurations. Section 4.2 describes measurement limitations for thin bonds.

4.0 DISCUSSION AND CONCLUSIONS

It is important to note that the limited number of specimens evaluated for each combination of material and the small inspectable surface area of one square inch for each specimen prevented a determination of statistical trends that may be present in bonded areas of larger parts. Trends observed were restricted to individual composite material systems and did not apply to other materials systems. Acoustic and mechanical properties are discussed and compared in bar chart form in the following sections.

4.1 Graphite Epoxy-Titanium

Comparisons between groups of specimens with thick "wet" adhesive bonds with excessive porosity, and groups of specimens with thick "dry" adhesive bonds, showed a noticeable trend for average acoustic parameters which correlated with average mechanical properties (see Figures 9 and 10). No complete separation occurred, however, in acoustic parameters that consistently separated "dry" from "wet" bonds in the moisture range evaluated. There was no correlation of these acoustic parameters, which would permit a reliable judgment as to specimen lap shear strength. An example of this situation occurs between two specimens with the same acoustic parameters. Specimen number 23 (with excessive porosity) failed at 3206 psi and specimen number 10 (without excessive porosity) failed at 5290 psi (see Appendix for data).

Another illustration of this problem is visible in data from specimen number 6. This specimen failed earlier than any other specimen in stress durability testing but displayed an acoustic parameter similar to unfailed specimens numbers 4 and 5 (see Appendix).

Thick "wet" bonds did not experience drastic mechanical property reductions. One reason for this lack of discrimination may result from the close dimensional proximity of thin (0.003 to 0.004 in.) and thick (0.005 to 0.008 in.) bonds.

When comparing acoustic to mechanical property data, however, one potential relationship was noted. Specimens with thick, "wet" bonds, which had the largest acoustic parameters, also had the lowest mechanical properties (see Figure 9). Confirmation of this acoustic to mechanical property trend can also be seen in Figure 10 for specimens fabricated with adhesive selected for high as-fabricated bond porosity.

In other supporting programs, examinations were performed on metal-to-metal adhesive bonds and differences were noted in comparison to composite-to-metal bonds. One explanation for differences in acoustic behavior noted in the subject program is that for all metal bonds, the face sheet-adhesive signal is larger than the back sheet-adhesive signal (see Figure 11). The face sheet-adhesive signal is smaller than the back

sheet-adhesive signal for graphite epoxy-titanium bonds. The inverse relationship between mechanical properties and acoustic parameters probably results from the reversed amplitude relationship of the adhesive signals.

The acoustic parameter (resonant depth) for the four groups of graphite-titanium specimens, which have thin bond lines, are quite uniform (see Figures 9 and 10). The range of resonant depth and energy above resonance parameters is not large. The sensitivity of the measurement is not enough to separate this group of specimens, which have no process variants, from the other specimens with thin bond lines. This decrease in measurement sensitivity is most probably caused by the bandwidth limitation of the measurement system for thin adhesive bonds.

4.2 Fiberglass Epoxy-Aluminum

The strength of "wet" and "dry" specimens was different. The "wet" specimens failed in stress durability, and the dry specimens were removed from the test after 454 hours (see Figure 12). High porosity, which was not intentionally introduced, was associated with "wet" specimens only. This was the same effect observed for the graphite-titanium specimens. Moisture, which was the process variant, appeared to introduce porosity. When the mechanical test results, which showed large differences in mechanical strength between the "dry" and "wet" specimens, were compared to the spectrographic results, the acoustic parameters in each thickness class separated the "wet" from the "dry" specimens. The difference in acoustic parameters was not large but significant in this case because the parameters for each set of three specimens was uniform for each process variant group. Resonant depth values increased for the higher strength specimens. This is the effect observed for metal-to-metal specimens.

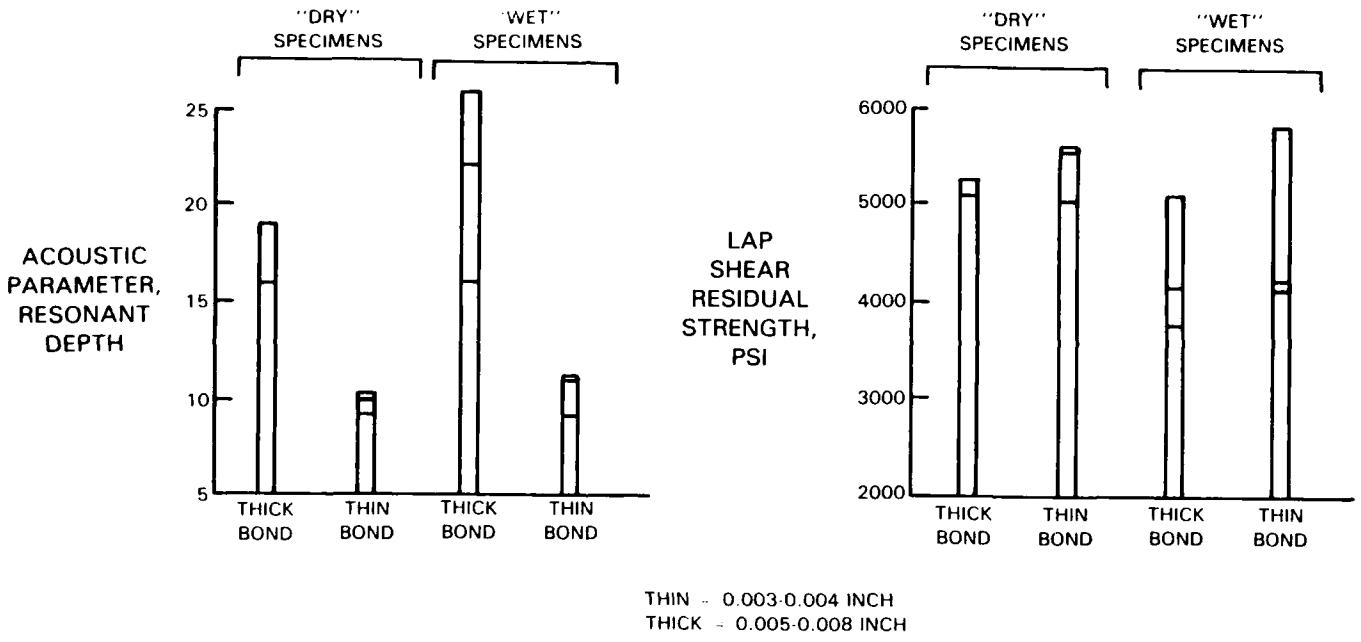
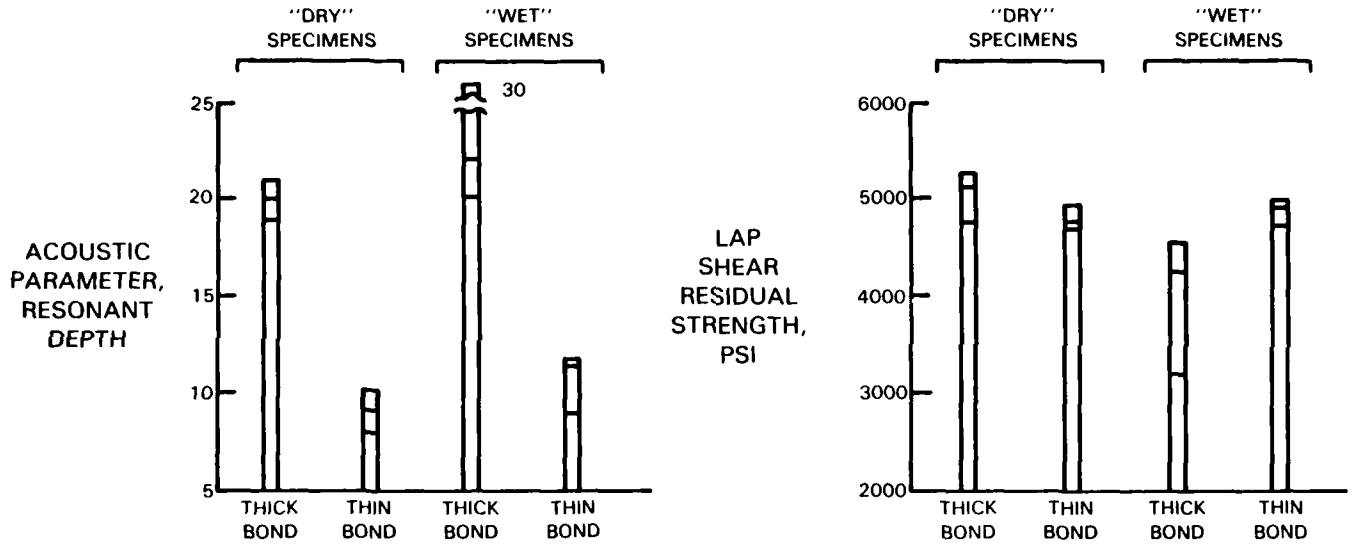


Figure 9 Graphite Epoxy-Titanium Lap Shear Specimens - Adhesive Selected for Low As-Fabricated Bond Porosity (Mechanical and Acoustic Test Results)

COMPARISON OF ACOUSTIC AND MECHANICAL TEST RESULTS



THIN = 0.003-0.004 INCH
THICK = 0.005-0.008 INCH

Figure 10 Graphite Epoxy-Titanium Lap Shear Specimens - Adhesive Selected for High As-Fabricated Bond Porosity

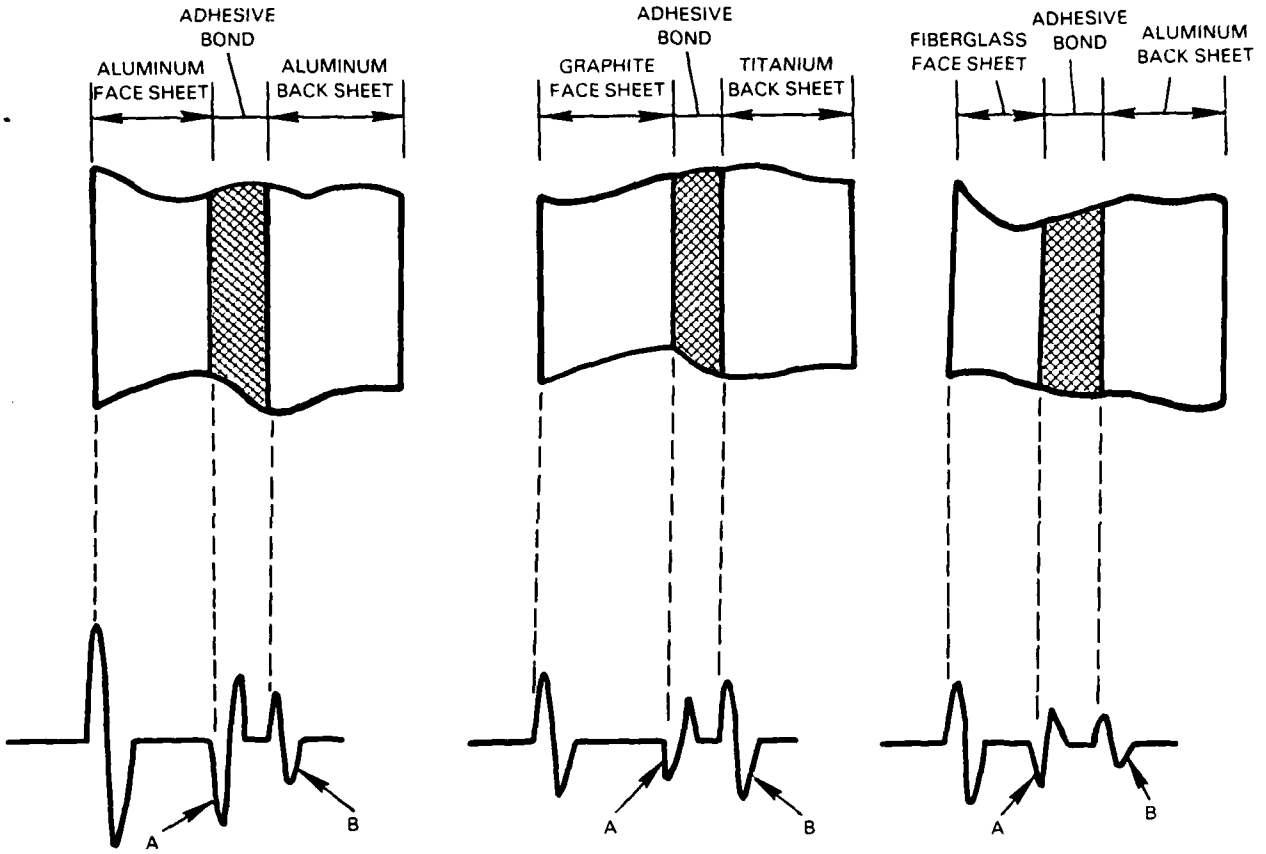


Figure 11 Comparative Acoustic Signals for Graphite Epoxy and Fiberglass Epoxy to Metal Joints - Adhesive bond signals for graphite-titanium specimens have a different amplitude relationship than the signals for figerglass-aluminum; i.e., for graphite-titanium (A) is less than (B) compared to fiberglass-aluminum where (A) is greater than (B).

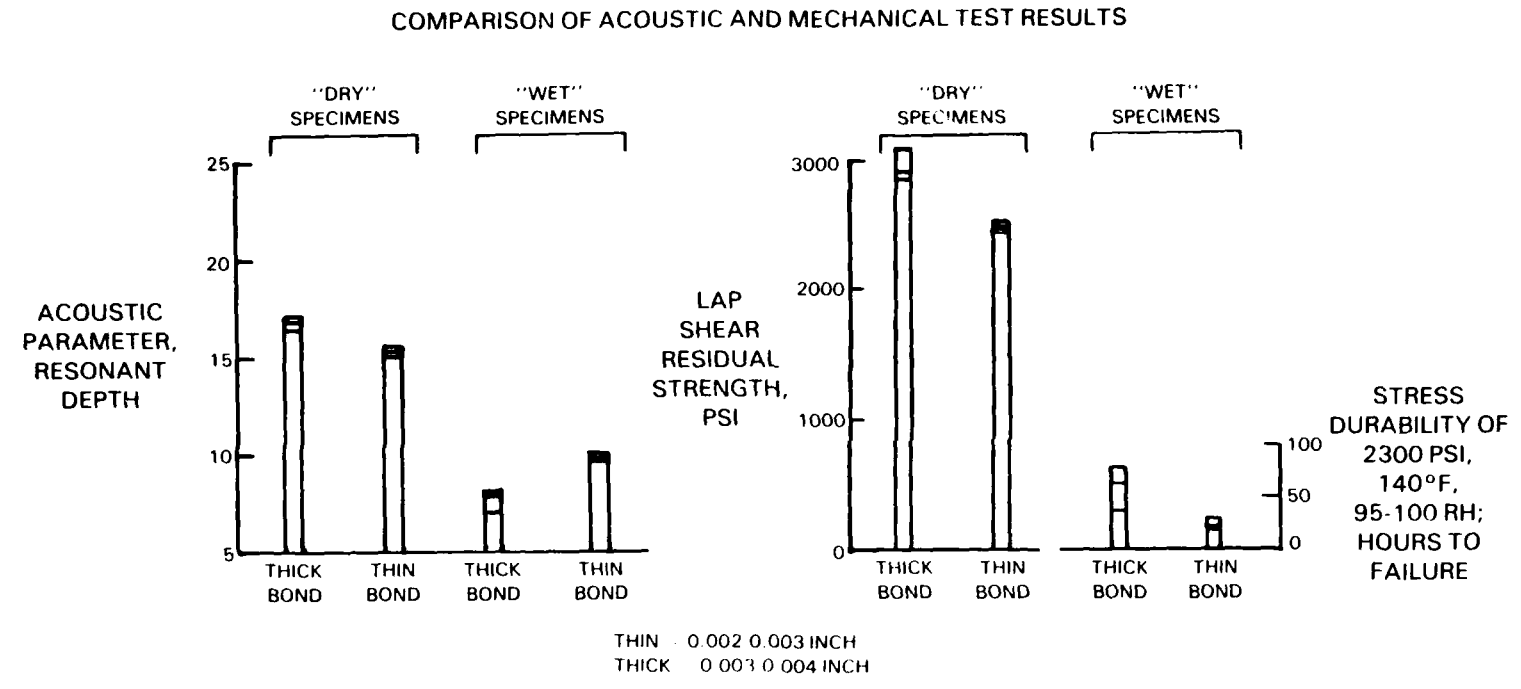


Figure 12 Fiberglass Epoxy-Aluminum Lap Shear Specimens

5.0 DEVELOPMENT PLAN FOR PROTOTYPE ADHESIVE INSPECTION SYSTEM

A plan for a computerized adhesive inspection system, which would use acoustic spectroscopy for signal analysis, was developed. This plan describes the requirements for a measurement system which would measure the parameters of an ultrasonic spectroscopic signature of an acoustic signal. The measurement system would read out mechanical properties which are known to correlate with the measured acoustic parameters. Flynn[1] and Chang[2] have shown that adhesive strength and adhesive thickness are related to ultrasonic spectroscopic parameters measured on adhesively bonded metal-to-metal specimens. This system is currently only practical for use on metal-to-metal bonds if the adhesive signals are separate from other possible interfering signals.

The description of the measurement system consists of two parts:

(1) Instrument hardware
(2) System software

The instrument hardware would consist of four main functional modules:

(1) Signal selection
(2) Signal analysis
(3) Signal conversion
(4) Digital processing and system control.

Each of these modules will be described in the following plan at the submodule or device level.

The system software would consist of two main functional components:

(1) Input parameters
(2) Modes of operation.

These components will be described at the subroutine level.

Each main part of this plan will also describe, where applicable, how its associated function carries out the practical aspects of spectroscopic measurements.

The instrument (see Figure 13), together with its associated software, is designed to form a measurement system capable of accepting input parameters, measuring spectral data, and reducing this information to numerical values that measure adhesive bond thickness and strength. Once the measurement parameters have been selected, the measurement system can be used for repetitive testing with a minimum amount of system operator intervention.

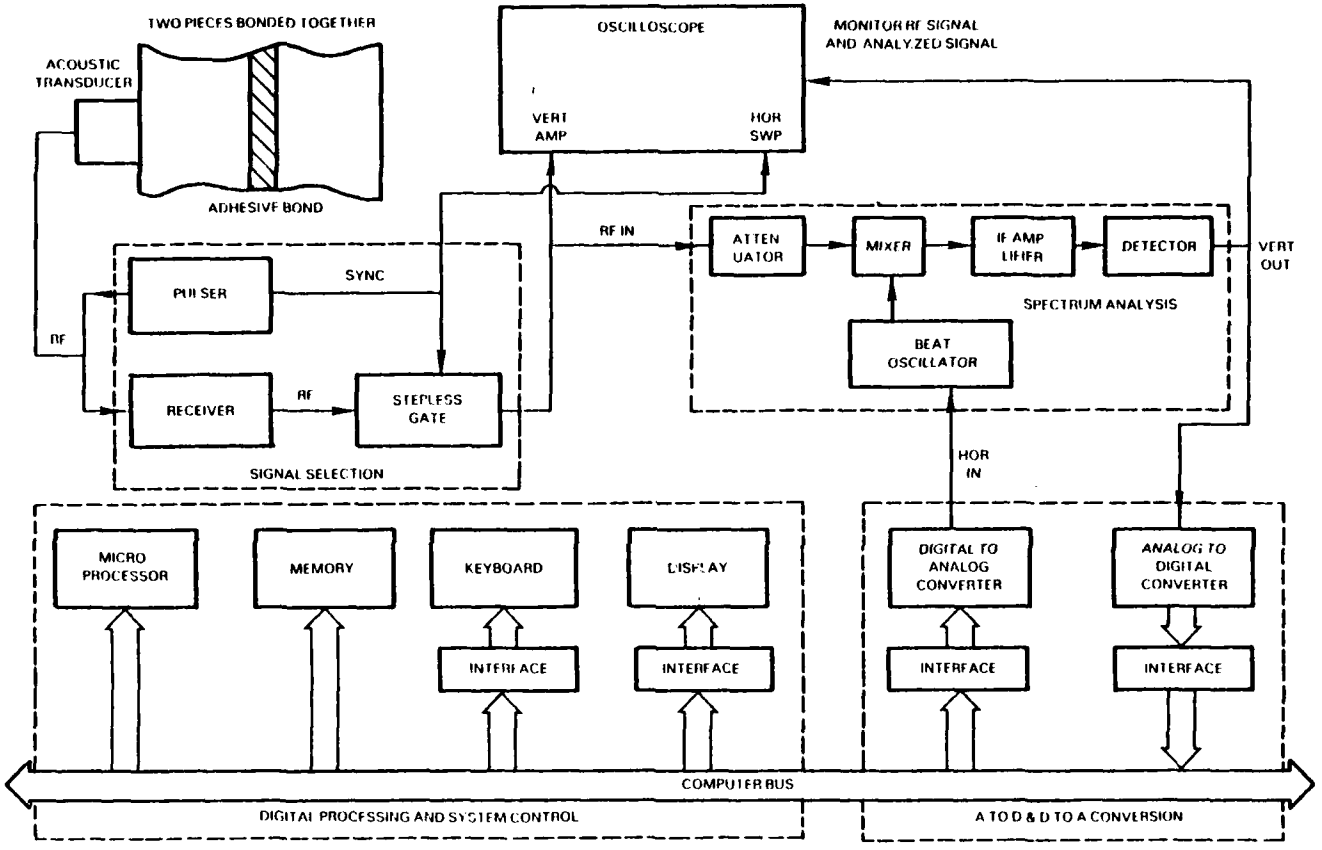


Figure 13 Block Diagram, Acoustic Spectroscopy Instrument

5.1 Instrument Functional Description

The analysis of acoustic signals requires an instrument that would comprise these functional modules:

(1) Signal selection

(2) Spectrum analysis

(3) Analog to digital converter and digital to analog converter interfaced to a computer bus

(4) Digital Processing and system control.

The function modules would be used to generate the electrical signals, analyze the selected signal, measure the analyzed signal, and implement the software algorithms. An oscilloscope would be necessary to monitor the selected signal and the analyzed signal.

5.1.1 Signal Selection

Three devices are required to implement signal selection:

(1) Pulser
(2) Receiver
(3) Stepless gate

The pulser generates the impulses to the acoustic transducer, which converts this electrical energy to acoustic energy. The acoustic signals, which return from adhesive bond interfaces, are converted back to electrical signals and are amplified by a receiver amplifier. The output of the receiver amplifier contains a series of signals that are return echoes from the various interfaces within the adhesively bonded structure. A stepless gate would allow the instrument operator to select those signals which contain information characteristics of the adhesive bondline. These selected signals would be analyzed by the spectrum analysis module and simultaneously monitored with an oscilloscope during the initial setup of the instrument.

5.1.2 Spectrum Analysis

Spectrum analysis transforms the selected signal, which is in the time domain, into the frequency domain. The individual frequency (spectral) components, which constitute the original complex waveform, would be displayed on a component amplitude versus component frequency graph (spectrum).

The functional module, which implements the spectrum analysis, would consist of five devices:

(1) Attenuator
(2) Beat oscillator
(3) Mixer
(4) Intermediate frequency amplifier
(5) Detector

The attenuator reduces the selected signal amplitude so that succeeding devices would not operate beyond their normal signal levels. The beat oscillator frequency would be controlled by the software program via a digital to analog converter. The mixer heterodynes the selected signal with the output frequency of the beat oscillator. The output of the mixer drives the intermediate frequency (IF) amplifier. The IF amplifier passes signals proportional to the spectral component amplitude, with a frequency equal to the beat oscillator frequency minus the input (selected signal) frequency. The output of the IF amplifier drives the detector, which provides a static voltage proportional to the IF signal amplitude. The output of the detector would be monitored with an oscilloscope and connected to the analog to digital converter.

5.1.3 Analog-to-Digital and Digital-to-Analog Conversion

Digital computers cannot process analog signals. An analog to digital (A to D) converter is a device that would be necessary to implement the conversion of the analog output of the spectrum analysis module to an equivalent digital signal. The reverse process, which utilizes a digital to analog (D to A) converter, is required to implement computer control of the beat oscillator frequency. Both devices must be compatible with a computer, and this can be accomplished by means of a digital interface to the computer's input/output bus.

5.1.4 Digital Processing and System Control

The digital computer would comprise four devices:

(1) Microprocessor
(2) Memory
(3) Keyboard
(4) Display

The microprocessor is the controlling device for the measuring system. This device implements the instructions, which are coded into the software. These instructions would allow the microprocessor to control the A to D converter and the D to A converter. All of these devices in conjunction with the spectrum analysis module, measure the acoustic spectrum.

As the spectrum data is measured, it would have to be stored for retrieval at some other time. A memory device, which is an integral part of any computing system, would be necessary to perform the storage function. The memory device would also be used to store the software.

The communication link between a human operator and the measurement system would require a keyboard device and a display device. The keyboard allows the operator to initiate software functions, and the display returns system responses.

5.2 Software for Spectrum Analysis of Acoustic Signals

The software, together with its associated hardware, is designed to form a measurement system capable of accepting input parameters and measuring data, and reducing this information to numerical values of adhesive bond thickness and strength.

The acoustic spectrum is the primary form of data. The three features of an acoustic spectrum releated to adhesive bond thickness and strength are:

(1) Frequency difference between two resonant depths (bond thickness)
(2) Resonant depth (bond strength)
(3) Average power in spectrum between two frequencies (bond strength)

The organization of the algorithms to implement these measurements and other instrument functions would be both flexible and convenient. Flexibility can be assured if modes chosen may be made in any order. Convenience can be implemented by allowing the system operator to predetermine the sequence of operations so that repetitive tests may be made with minimum operator intervention.

5.3 Software Requirements

Before testing is initiated, system parameters must be entered into the program by the operator. This procedure is necessary so that the constants correspond to the analysis frequency range and the full-scale frequency range of the spectral analysis module. This operation would be required whenever the analysis parameters are changed.

Four modes of operation (analyzer adjustment, setup, test, and stop) are required to implement the measuring system functions. Each mode must be independently accessible from the operator's perspective. After each mode is completed, the program must enter a ready state such that the operator would always be capable of choosing another mode.

The program generates the control signal to the spectral analysis module. The analyzer adjustment mode would be required to generate control signals corresponding to the end points of the control range. This mode permits manual adjustments to be made to the measuring system to provide for compatibility between the hardware and the software.

The setup mode would be required to present to the operator a list from which to choose spectral operations. These operations would be capable of acquiring spectral data, performing mathematical calculations with the data, and allowing the results of these calculations to be calibrated against adhesively bonded standards of known thickness and strength.

The test mode would be required to remember the sequence of operations, which were chosen in the setup mode, and to perform these operations on command by the operator.

The stop mode would be required to halt the measuring system and return the software to the ready state without altering previously acquired data.

5.4 Description of Program Initiation

The frequency parameters of the spectrum would be input to the program by means of an interactive dialogue with the operator. The spectral parameters required are: first frequency, last frequency, and full scale frequency. The program would then enter the ready state, from which the operator may choose the measuring system functional modes.

5.5 Description of Program Modes

5.5.1 Analyzer Adjustment Mode

The analyzer adjustment mode would allow the operator three choices:

(1) Set the spectrum analyzer for zero frequency
(2) Set the spectrum analyzer for full scale frequency
(3) Enter the ready state.

Choices 1 and 2 would alternately allow the operator to adjust the spectrum analyzer such that the output signals of the computer would be compatible with the input requirements of the analyzer.

5.5.2 Setup Mode

The setup mode would require an interactive selection of operations that would be implemented in the test mode. As each operation is selected, the operator would enter constant values (where appropriate), which would set the calibration of the measuring system. These operations (in the order to be selected) are:

(1) Choose the spectrum (measured or reference) which would be measured.

(2) Normalize the spectral data which has just been acquired.

(3) Deconvolute the measured spectral data (not applicable to reference spectrum)

(4) Smooth the spectral data.

(5) Delta frequency calculation (print result)

(6) Resonant depth calculation (print result)

(7) Area of spectrum calculation (print result)

Data Manipulation

Spectrum. Operation Spectrum would enable the system operator to collect either the measured spectral data or the reference spectral data when the test mode is entered.

Normalize. Operation Normalize multiplies each frequency component of the spectrum by a constant, which would cause the maximum value of all normalized spectra to be the same value. The practical aspect of this operation is to compensate for the signal strength variations caused by variations in acoustic coupling between the transducer and the test piece.

Deconvolute. Operation Deconvolute would perform an algebraic subtraction between the respective spectral components of the reference spectrum and the measured spectrum. The data would have to be in the logorithmic form for this operation. The actual result of this operation would be a division of the measured spectrum by the reference spectrum. The practical aspect of this operation is to allow the operator to remove the effects of frequency response variations of the measurement system, including the acoustic transducer.

If the reference spectrum was chosen previously, the Deconvolute operation cannot appear as a choice.

Smooth. Operation Smooth would allow the operator to average out localized scatter in the spectrum data. This operation would be used by the operator if delta frequency or resonant depth had been selected and the results of these operations indicated that scatter in the spectral data was being recognized by the program as spectral features.

Calculation of Results

All of the previous operations would alter the spectral data if selected. The following operations would not alter the spectral data. If any of the following operations are selected, the operator would be allowed the option of entering a constant multiplier. This multiplier, subject to mathematical constraints, would allow for the conversion between spectral parameters and known adhesive parameters.

Delta Frequency. Operation Delta Frequency measures the frequency difference between two resonant depths of the spectral data. The program would scan the spectrum for two minimum amplitude values. The respective frequencies associated with these minima are then subtracted to obtain the resultant delta frequency.

Resonant Depth. The Resonant Depth function determines resonant depth, and would scan the spectral data for the first two maximum values. A straight line would then be constructed between these maximum values, and would then serve as the point of reference from which the resonant depth is measured. The function would determine resonant depth by scanning the spectral data for a minimum value between the two previously determined maximum values and then measure the vertical distance between the minimum value and the constructed line.

Area. Operation Area would allow the operator to integrate a particular area of the spectrum. The area would be calculated by totalizing the amplitude components between two frequencies. The first frequency would correspond to the frequency for the minimum value, which would be determined in the same manner as described for Resonant Depth. The second frequency would be entered by the operator at the time Operation Area is selected. If no entry is made at this time, the full scale frequency would be substituted by the program for the second frequency.

5.5.3 Test Mode

The test mode would perform all the operations that were previously chosen by the operator. The practical implication of this scheme is the convenience of minimal button-pushing operations when taking many measurements. The computer would print the operations and the results of the computations that were selected in the setup mode each time the test mode is entered. The program would then automatically return to the ready state from which the operator may select any mode.

5.5.4 Stop Mode

The stop mode would allow the operator to interrupt the test in progress without destroying the reference spectral data. The program would automatically be returned to the ready state.

LIST OF REFERENCES

1. Chang, F.H. and J.R. Bell, "Adhesive Bond Inspection by Ultrasonic Spectroscopy NDT," ASM - Proc. of Material Conf., October 1977.

2. Flynn, P.L., "Cohesive Bond Strength Prediction for Adhesive Joints," Journal of Testing and Evaluation, JTEVA, Vol. 7, No. 3, May 1979, pp. 168-171.

APPENDIX

TABULATION OF LAP SHEAR BOND STRENGTH AND ULTRASONIC DATA

	Spec No	Mechanical Strength, psi	Resonant Depth*	Spec No	Mechanical Strength, psi	Resonant Depth	Spec No	Mechanical Strength, psi	Resonant Depth	Spec No	Mechanical Strength, psi	Resonant Depth
Low Humidity "Dry" Specimens	1	5544	10	4	5063	18	7	4710	6	10	5290	20
	2	5043	10	5	5281	15	8	4759	10	11	4778	22
	3	5616	8	6**	-	18	9	4950	8	12	5123	18
	Avg	5400	9		5172	17		4806	8		5063	20
High Humidity "Wet" Specimens	13	5731	12	16	3771	27	19	4913	8	22	4535	24
	14	4204	8	17	5071	17	20	4753	13	23	3206	20
	15	4143	12	18	4157	24	21	4958	13	24	4279	30
	Avg	4692	11		4333	23		4874	11		4006	25
	50 lb/in^2 load-thin bond			5 lb/in^2 load-thick bond			50 lb/in^2 thin bond			5 lb/in^2 load-thick bond		
	← Specimens Without Intentional Porosity →						← Specimens With Intentional Porosity →					

* Unit less number

** Failed early in stress durability in 9 hours.

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FOR BOND STRENGTH USING ULTRASONIC SPECTROSCOPY
T. J. Igielski, S.S. Blecherman and J.E. Doherty
Pratt & Whitney Aircraft Group, Government Products Division

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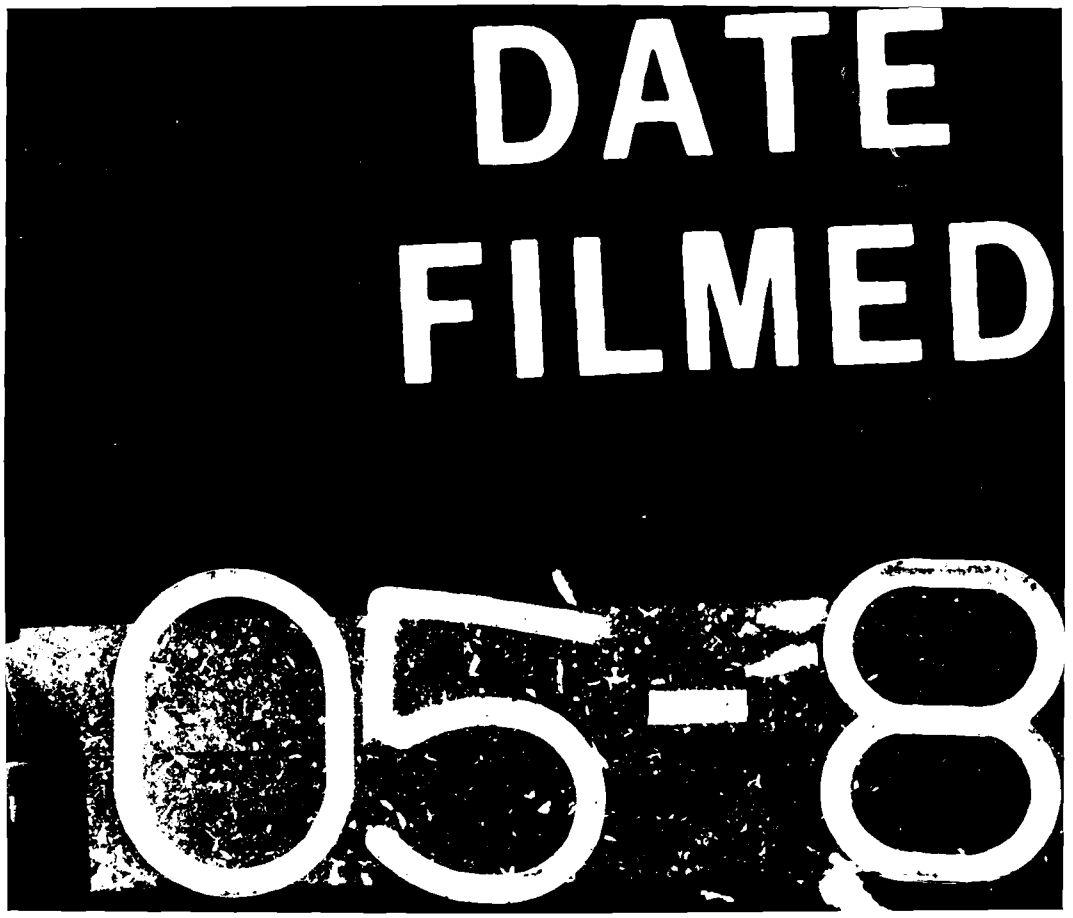
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